Fusion State of Play and R&D Considerations for the CSS

Matteo Barbarino

Fusion Science Technical Lead

IAEA Department of Nuclear Sciences and Applications

Special session on fusion at CSS-59

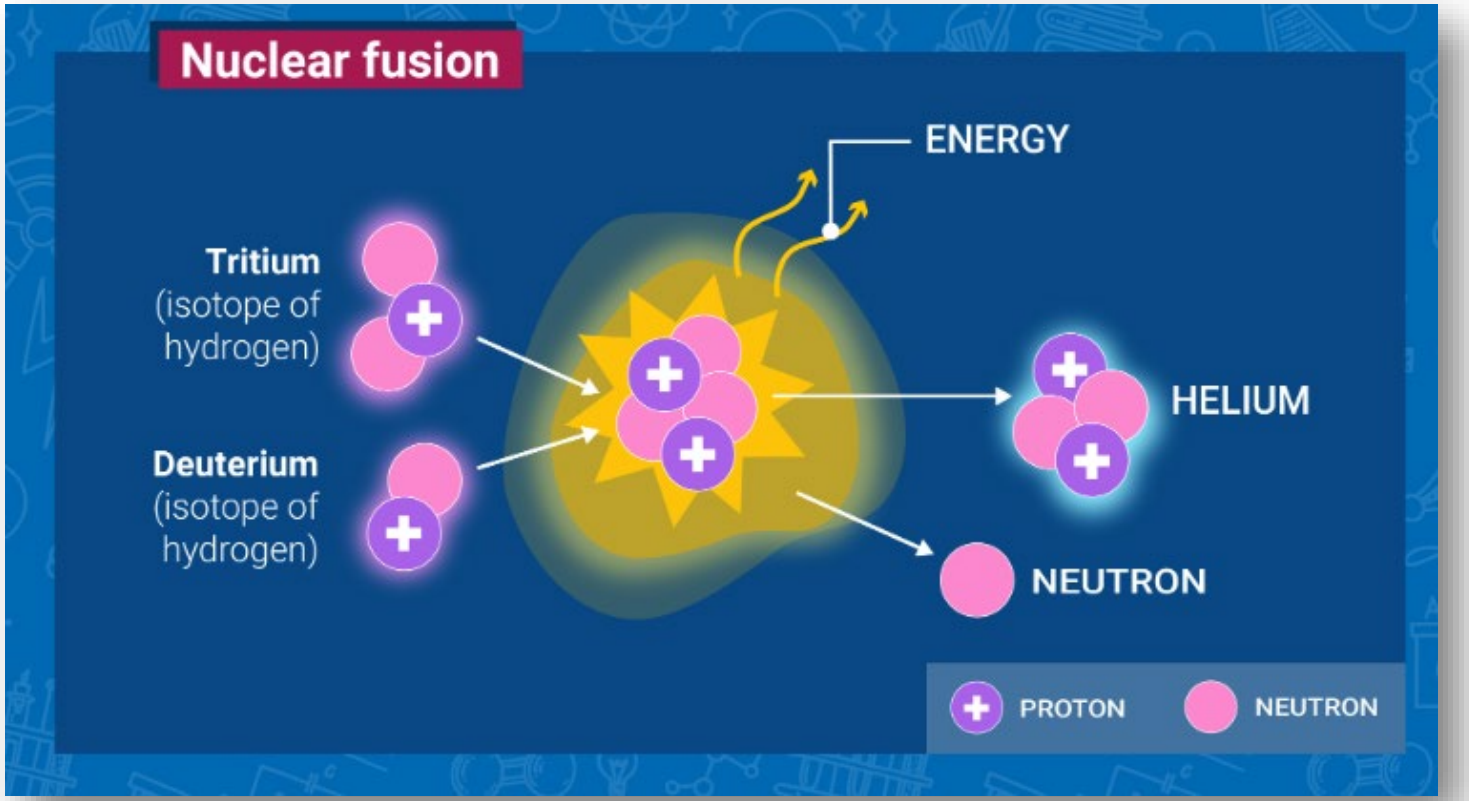
16 March 2026



The Nuclear Fusion Reaction/1

Fusion is a physical process that releases a lot of energy

- Fusion combines **light nuclei** to release energy
- Energy gain **450:1**
- Requires plasma temperatures **>150 million °C**
- **Fuel (abundant)**: e.g., deuterium, tritium, lithium, helium 3, boron

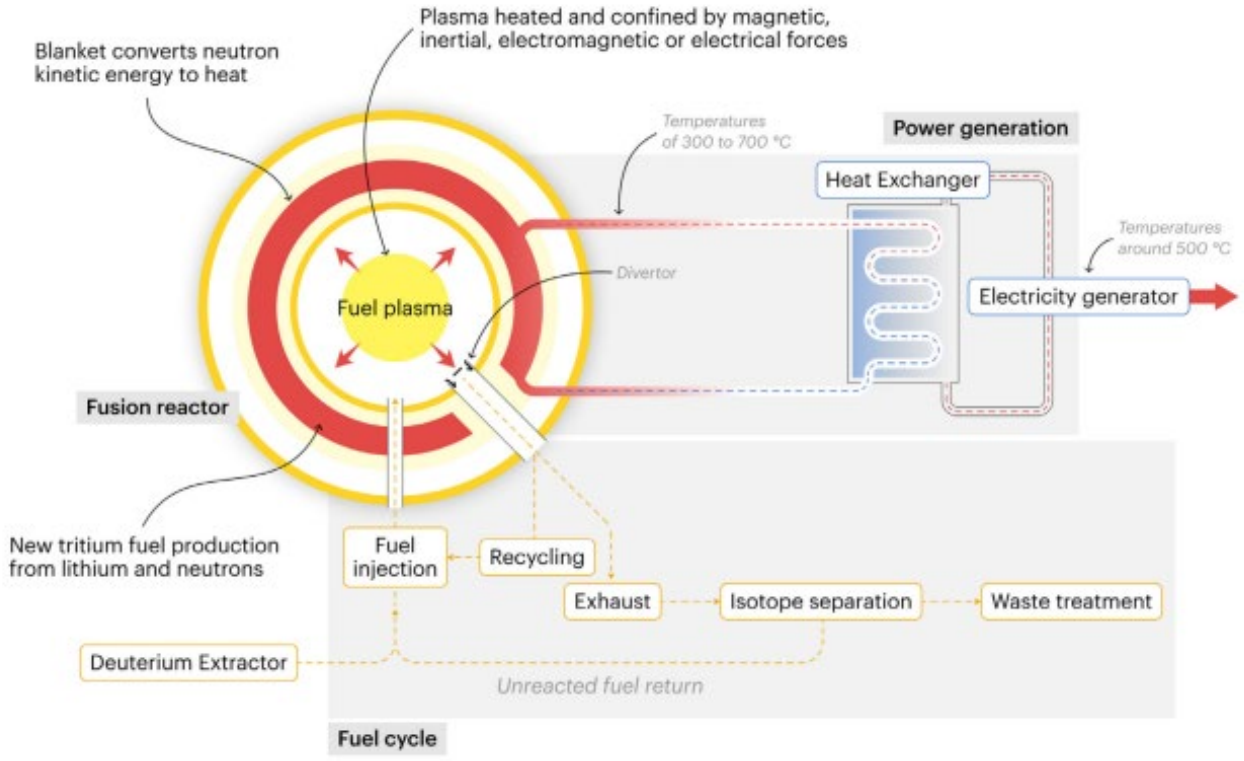


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The Nuclear Fusion Reaction/2

Fusion is a physical process that releases a lot of energy

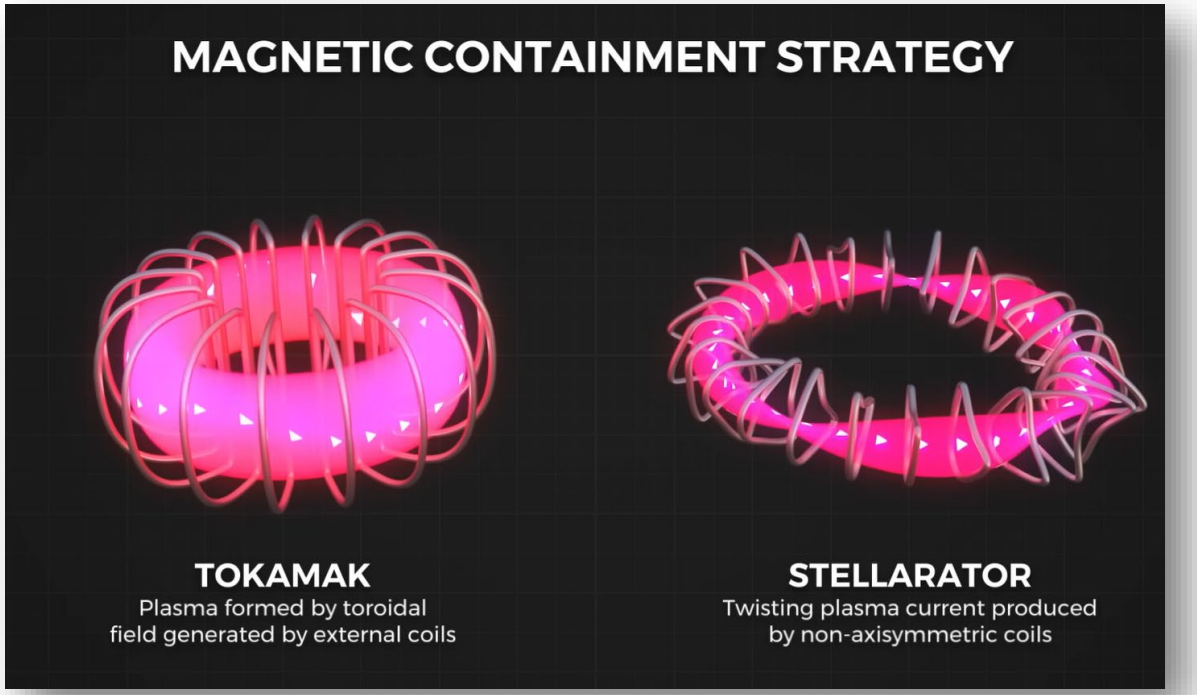
- **No fissile material**
- **No self-sustaining chain reaction** (fusion requires active plasma confinement)
- **No long-lived radioactive waste** (such as actinides or fission products)
- **Primary radiological hazards:**
  - Tritium
  - Neutron activation products (limited residual heat after shutdown)



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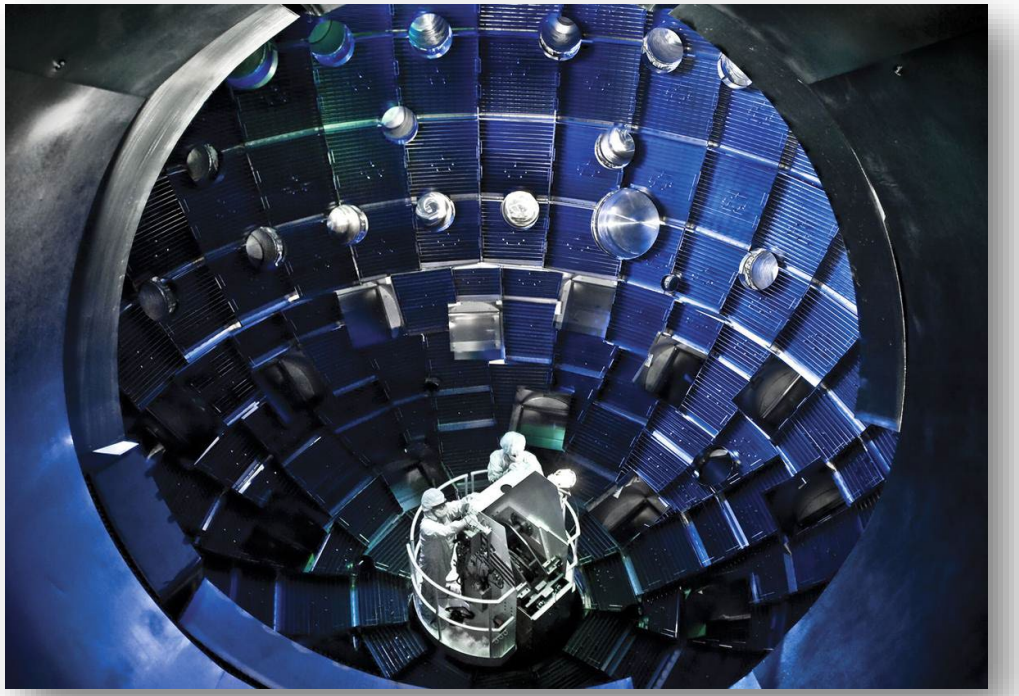
Two main approaches

Magnetic Fusion Energy



IPP (Germany)

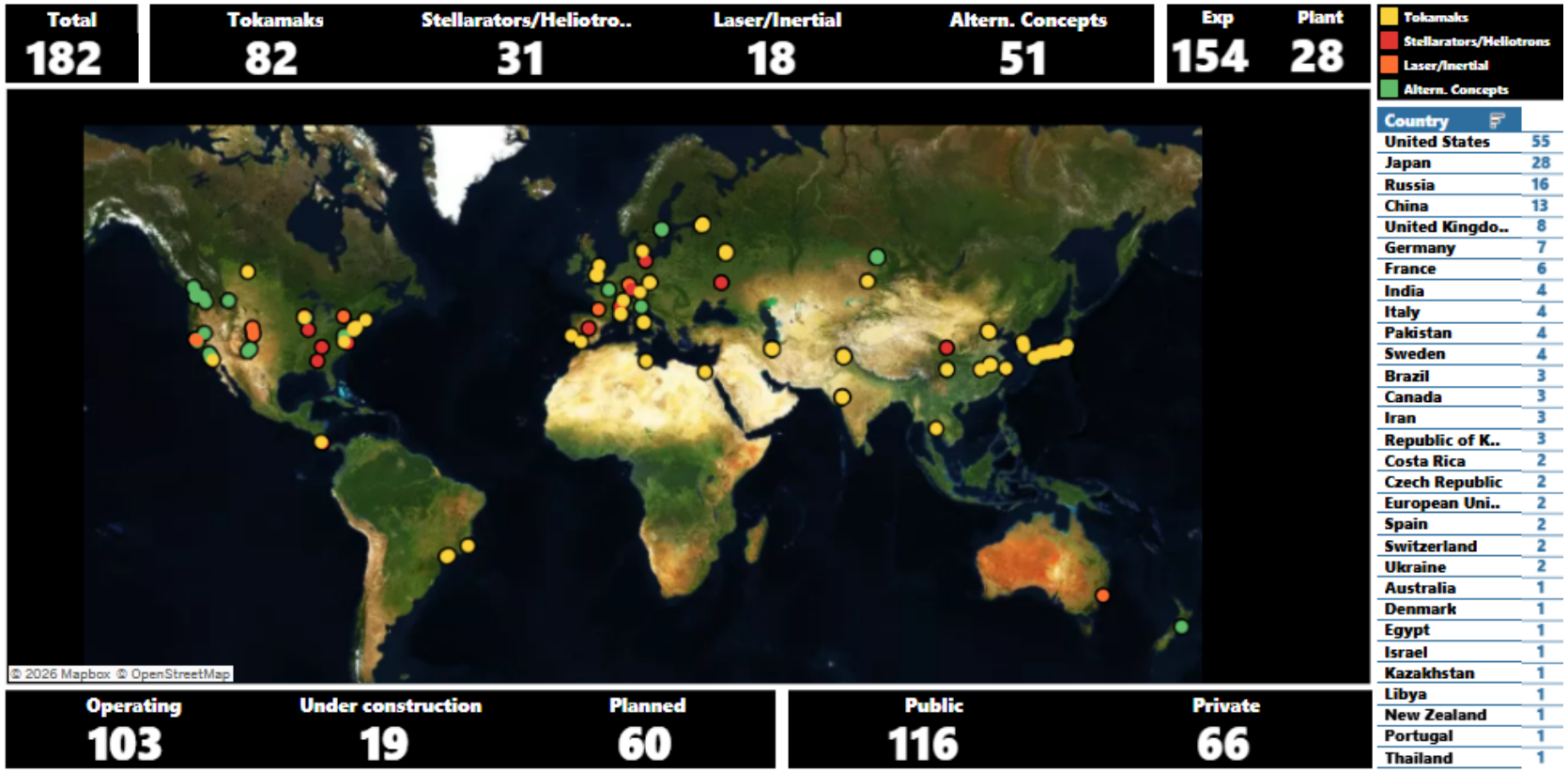
Inertial Fusion Energy



LLNL/NIF (USA)

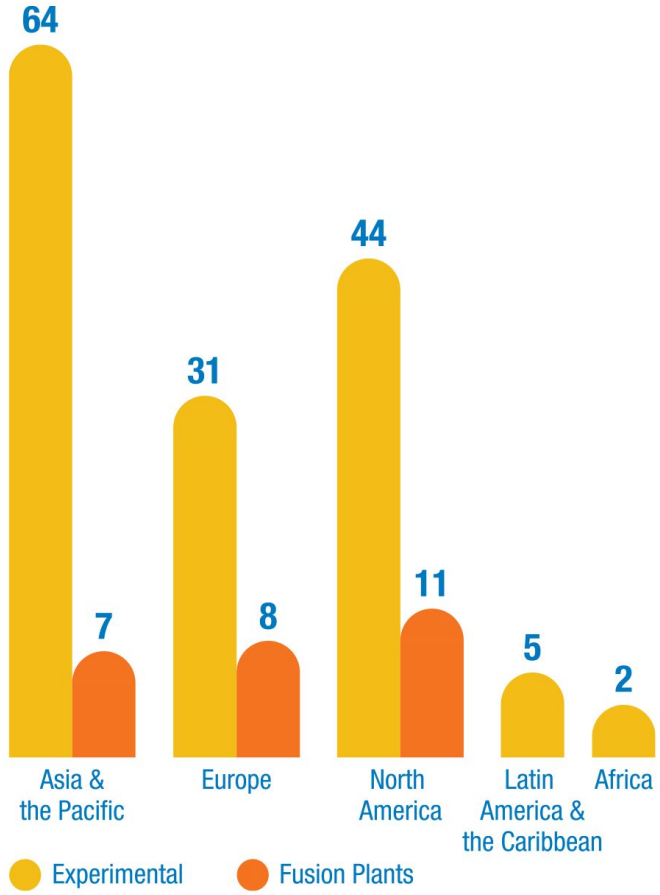
180+ fusion machines worldwide

Mix of public and private projects



Country	
United States	55
Japan	28
Russia	16
China	13
United Kingdo..	8
Germany	7
France	6
India	4
Italy	4
Pakistan	4
Sweden	4
Brazil	3
Canada	3
Iran	3
Republic of K..	3
Costa Rica	2
Czech Republic	2
European Uni..	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
Israel	1
Kazakhstan	1
Libya	1
New Zealand	1
Portugal	1
Thailand	1

IAEA Fusion Facility Database



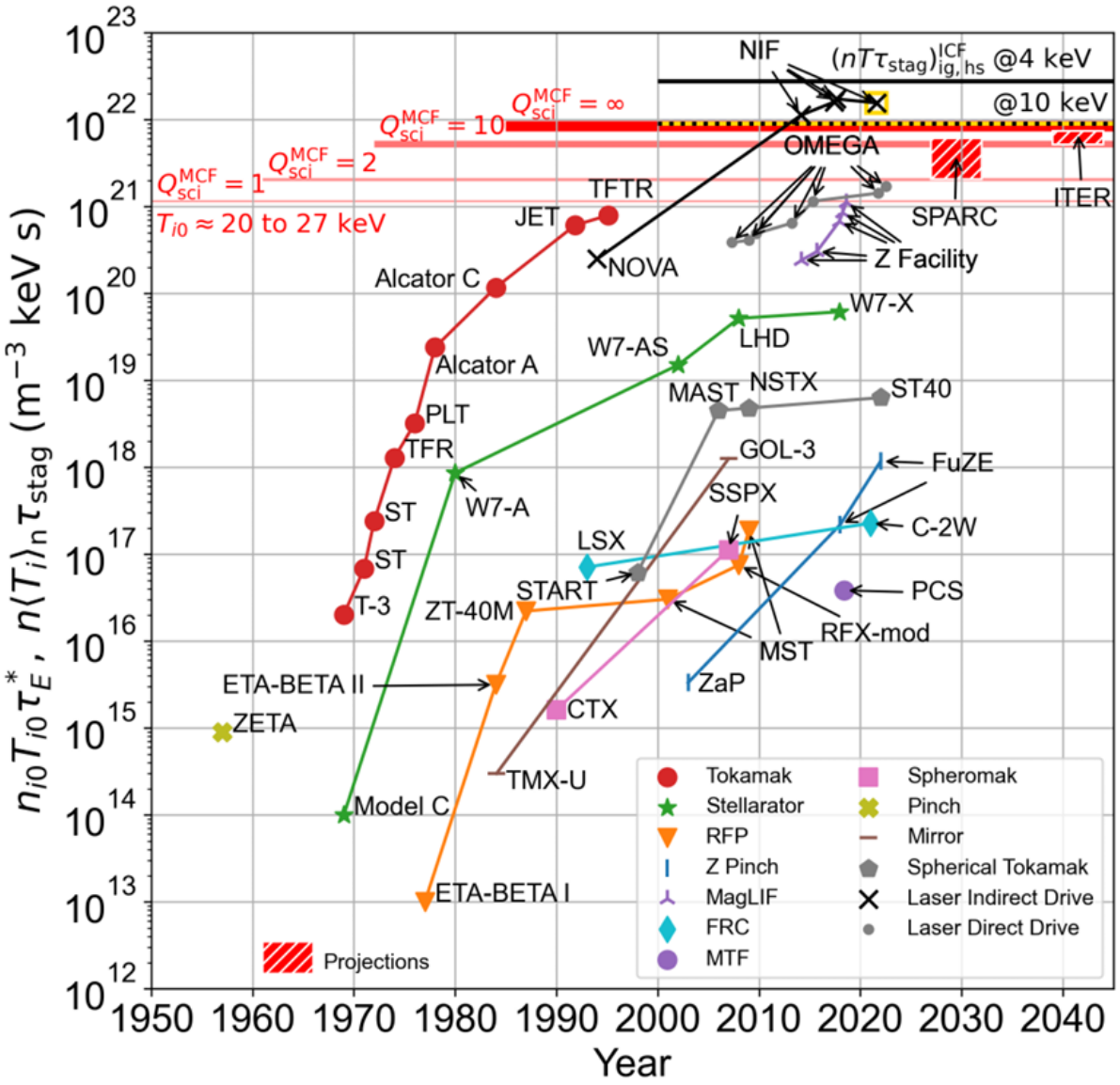
IAEA WFO 2026

Fusion state of play/1

Major progress achieved (physics confinement, modelling, technology design)

Understanding performance:

- **Triple product** = key performance metric
- **Q** = P_{out}/P_{heat}
- **$100B invested** globally since the 1970s
- Annual public funding ~ **$3-4B**



S. Wurzel, S. Hsu (2025)

Fusion state of play/2

Fusion power plants are not yet imminent

Technical challenges remain:

- Cost
- Surface heat exhaust management
- Materials resistant to extreme conditions
- RAMI (reliability, availability, maintainability and inspectability)
- Tritium breeding and fuel cycle
- Overall efficiency

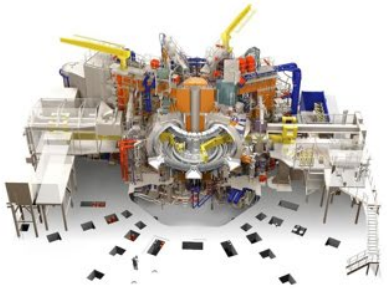


TORE SUPRA (WEST) D-D

P_{fusion} ~ 0

$P_{heating}$ ~ 15 MW

T_{plasma} ~ 1000 s *(Feb 2025)*



JET D-T

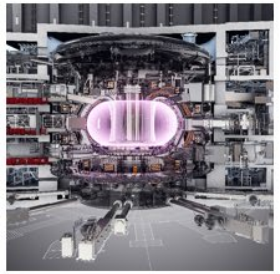
P_{fusion} ~ 15 MW (peak)

$P_{heating}$ ~ 25 MW

T_{plasma} ~ few s

$^{3}H_{inventory}$ ~ few g

W_{fusion} ~ few GJ



ITER D-T

P_{fusion} ~ 500 MW (steady)

$P_{heating}$ ~ 50 MW

T_{plasma} > 600 s

$^{3}H_{inventory}$ ~ kg

W_{fusion} ~ 10^{7} x JET



e.g. EU-DEMO D-T

P_{fusion} ~ 2000 MW

$P_{heating}$ ~ 50 MW

T_{plasma} > 7200 s

$^{3}H_{inventory}$ ~ tens of kg

W_{fusion} ~ 10^{2} - 10^{3} x ITER

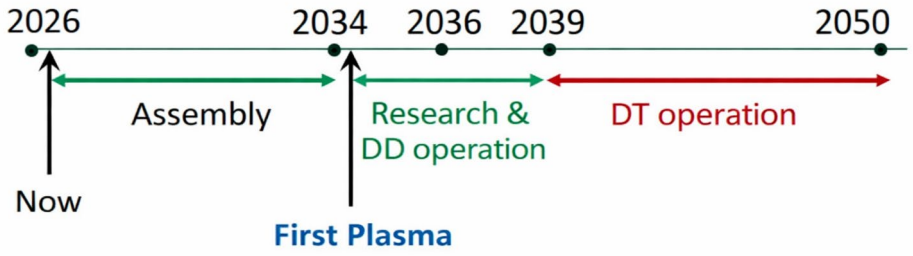
P. Barabaschi, IAEA General Conference (2025)

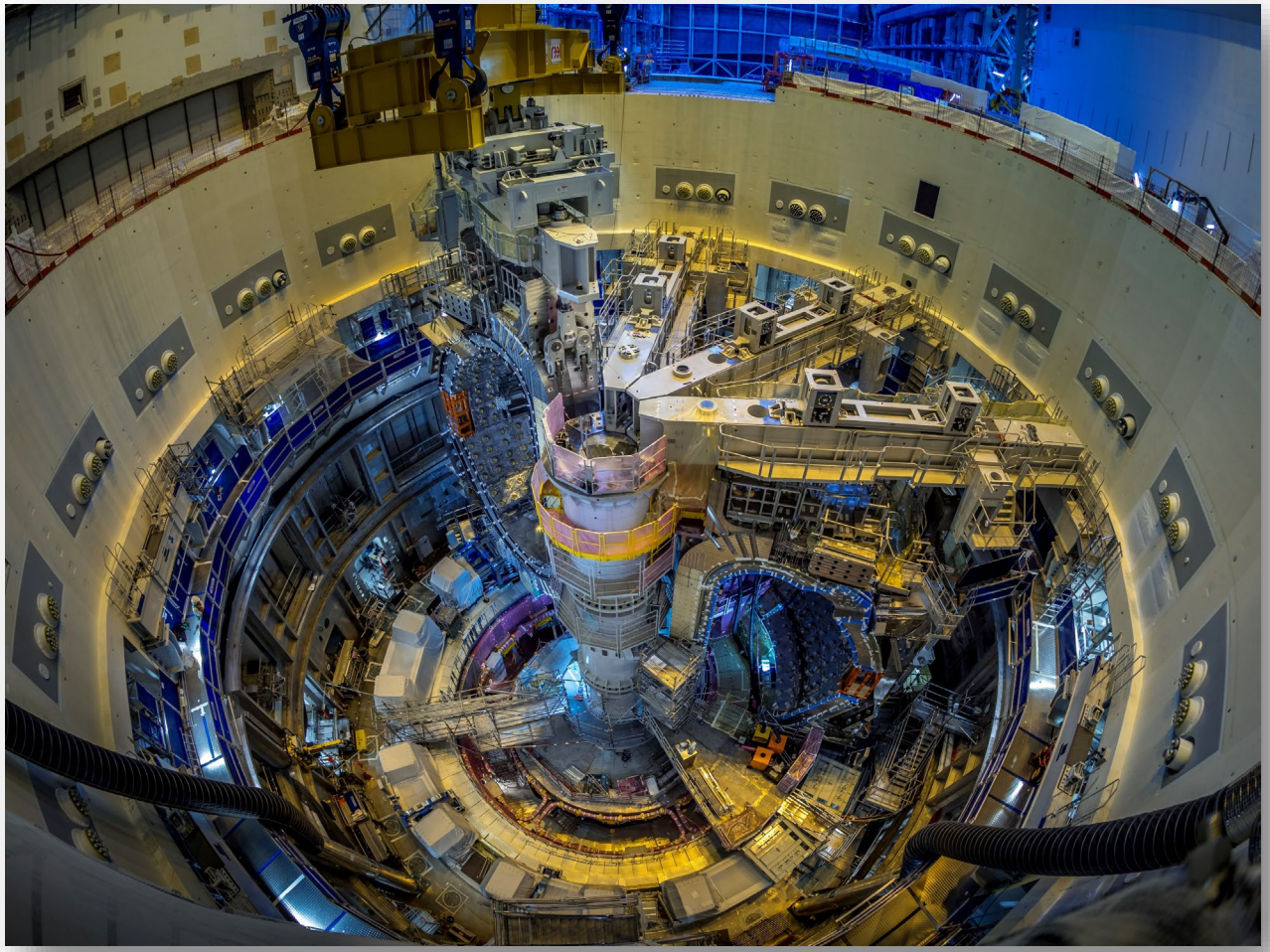
Fusion is one of the longest sustained global research efforts

ITER is the flagship international research project designed to de-risk the core science and enabling technologies required for future fusion power plants

China, EU, India, Japan, Korea, Russia, United States

- **Cornerstone of global fusion R&D** since the 1980s, anchoring the international research community
- **Catalyst for a global high-tech supply chain** across ITER Members
- **Improved project delivery**: in 2024–2025 ITER achieved more than 100% of planned schedule milestones



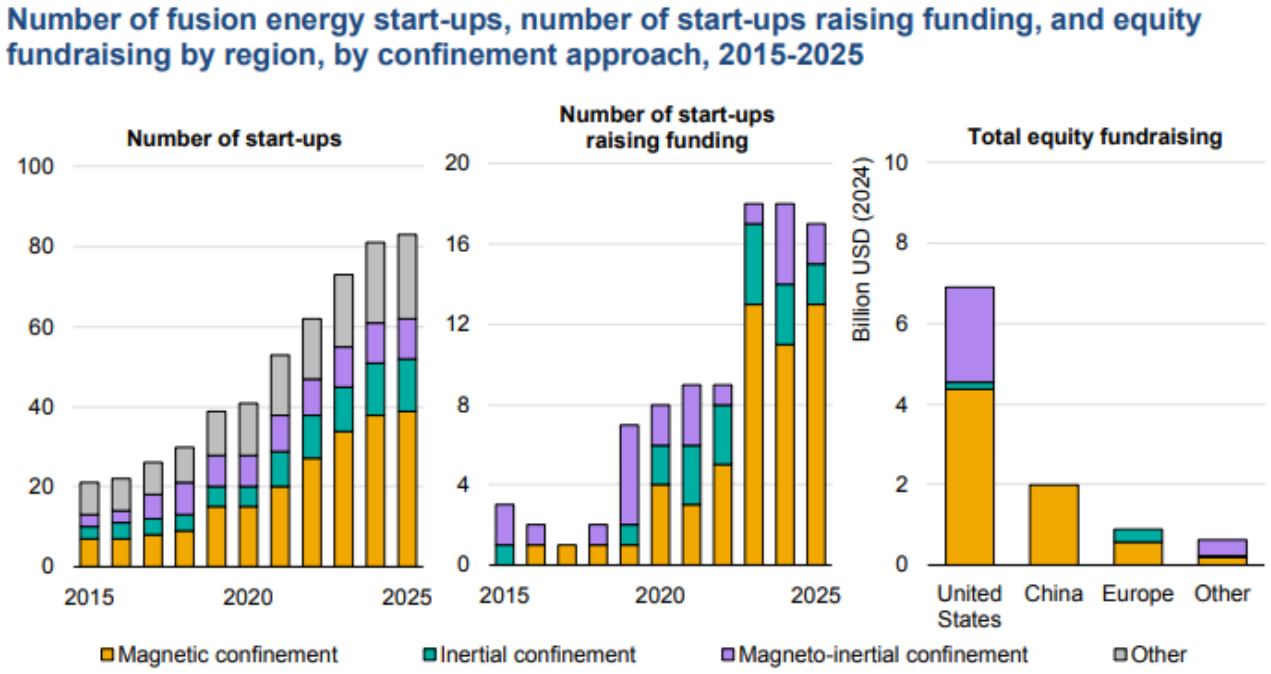


ITER Organization

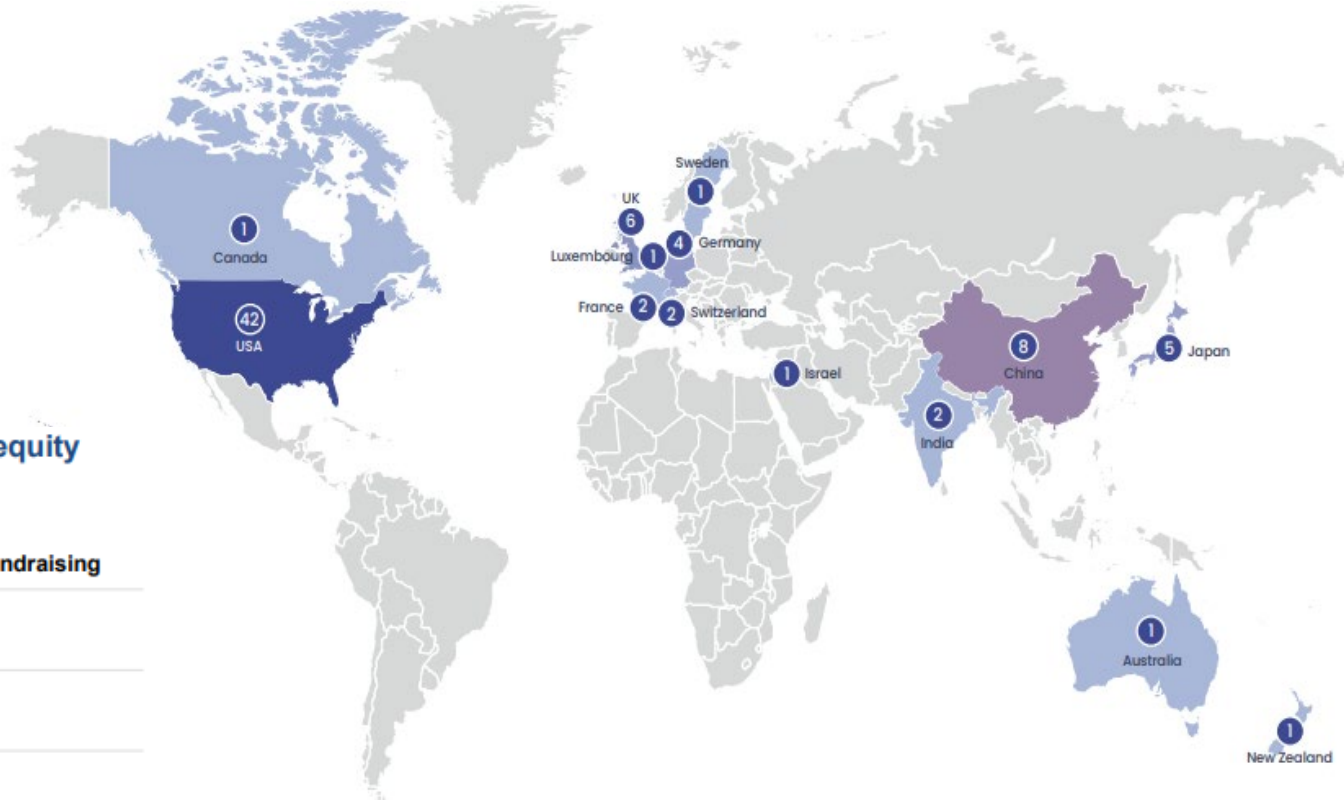
Growing private sector ecosystem

$10-15B raised since 2020

- 70+ private companies
- Most of the Venture Capital directed to ITER-like tech

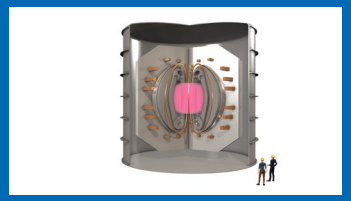
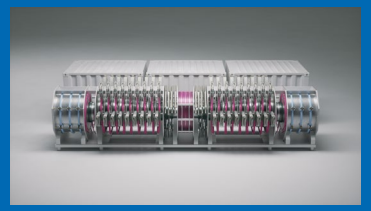
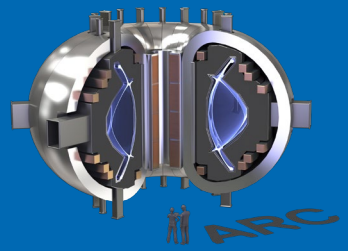


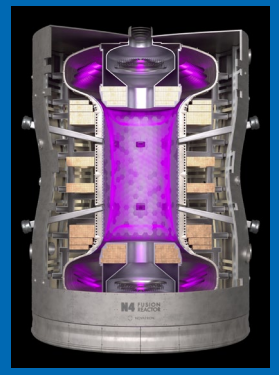
IEA The State of Energy Innovation 2026



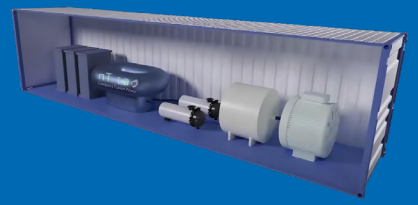
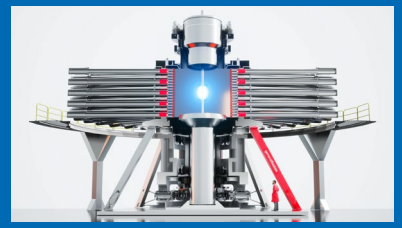
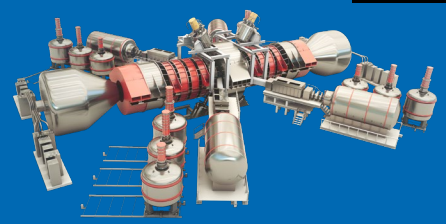
Fusion for Energy, Global Investment in the Private Fusion Sector 2025

Growing pipeline of fusion plant projects





IAEA WFO 2026

2020s

Commonwealth Fusion Systems (ARC), Helion Energy (Polaris/Orion)

2030s

Focused Energy (LightHouse), General Fusion (General Fusion Plant), Helical Fusion (Helical stellarator), Japanese Consortium (JA DEMO), Kyoto Fusioneering (FAST), Longview Fusion Energy Systems (Longview Fusion Energy Systems fusion plant), Novatron Fusion Group (N4), nT-Tao (Tao Machine), Proxima Fusion (Stellaris), TAE Technologies (Da Vinci), Tokamak Energy (Tokamak Energy fusion pilot plant), Type One Energy (Infinity Two)

2040s

Chinese Consortium (CFEDR), Gauss Fusion (Gauss GIGA), UK Industrial Fusion Solutions (STEP)

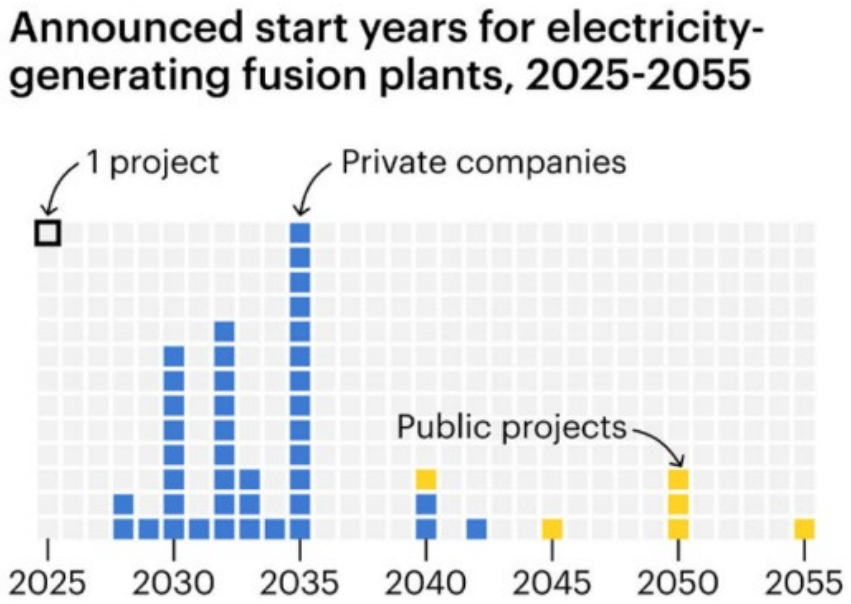
2050s

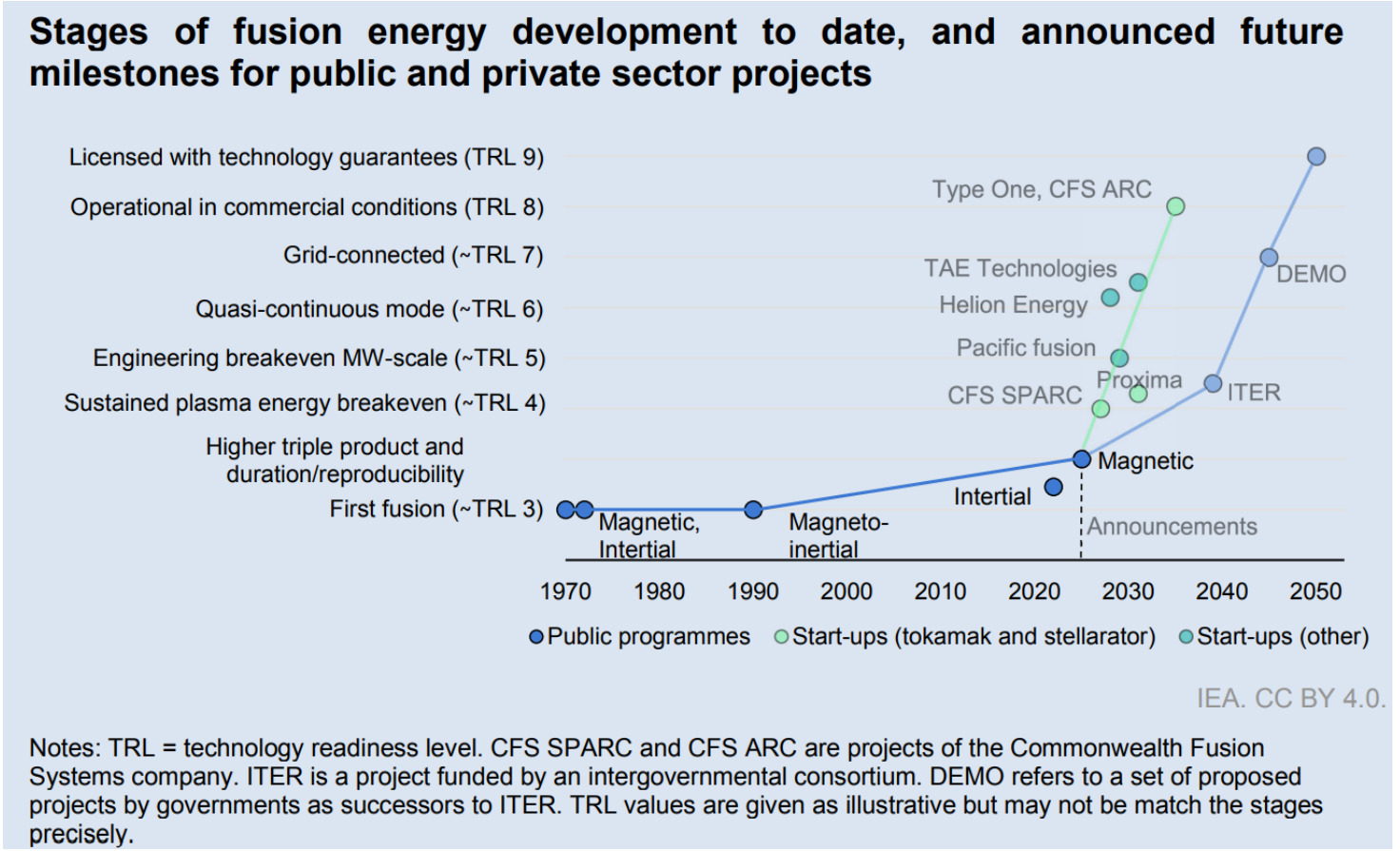
Russian Consortium (DEMO-RF)

Timeframe to be determined: EUROfusion (EU-DEMO), Korean Consortium (K-DEMO), Zap Energy (Zap Energy fusion plant)

Scaling-up : private vs public

Diverging perspectives on the levels and timelines of technological maturity





Notes: TRL = technology readiness level. CFS SPARC and CFS ARC are projects of the Commonwealth Fusion Systems company. ITER is a project funded by an intergovernmental consortium. DEMO refers to a set of proposed projects by governments as successors to ITER. TRL values are given as illustrative but may not be match the stages precisely.

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Areas where continued R&D is important

Further technical work needed to strengthen the knowledge basis for future safety considerations

- **Tritium measurement and accountancy** – nuclear data, quantification of inventories, permeation and retention in materials
- **Activation and waste characterization** – improved prediction of material activation and waste classification
- **Fusion fuel cycle systems** – tritium breeding, processing and handling at industrial scale
- **Dust behaviour and mobilization** – generation, transport and potential release mechanisms
- **Decommissioning methodologies** – management of activated/tritiated materials and facility dismantling

These topics represent areas where additional operational experience, manufacturing experience from large-scale components (e.g. ITER), and coordinated research can support future safety guidance.



Fusion Programme

The IAEA supports fusion development from research to deployment through three main pillars

- **DGO:** coordination
- **NA:** fusion and plasma research & development
- **NE:** fusion-fission synergies
- **NS:** fusion safety & regulation



The convener for the fusion community

World Fusion Energy Group

Driving policy dialogue

Rome, Italy 2024 and **Chengdu, China 2025:**

- **36 and 25 participating countries**, in Rome and Chengdu
- international organizations, private sector, various industries, investors

Technical sessions:

Financing, PPPs, R&D, Regulation, Supply Chains

WORLD FUSION ENERGY GROUP | For the Clean Energy Future

Fusion Energy Conference

Driving R&D collaboration and coordination

Chengdu, China 2025

- **50+ countries**
- international organizations, private sector
- 1000+ of participants
- 800+ contributions

Technical sessions:

Experiments, Theory, Technology, Materials

Next FEC: Seoul, Korea, 4-9 October 2027

FEC2025

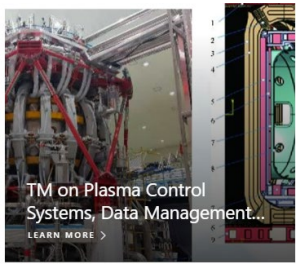
NA’s driving the fusion and plasma R&D agenda

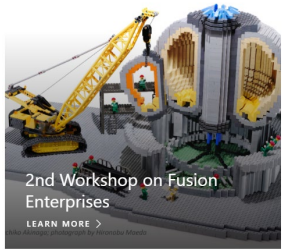
Global events focused on **fusion & plasma science and engineering** with major players and private sector engagement



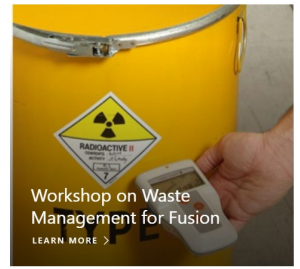


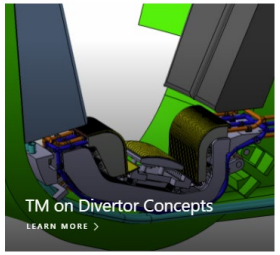




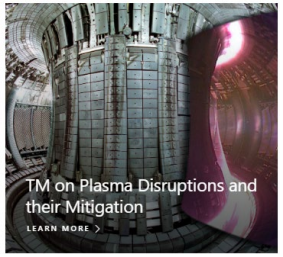




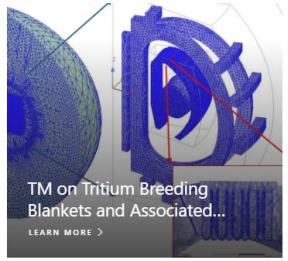










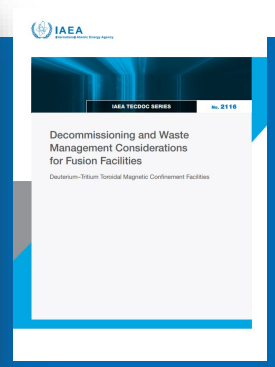


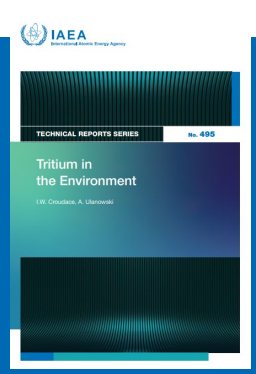


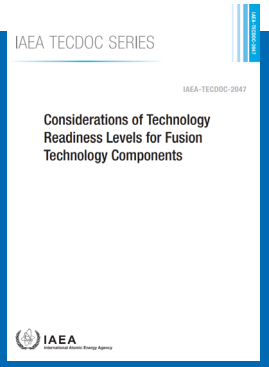
Complemented by key publications











NA’s preparing the future fusion & plasma workforce

Growing number of schools and training activities hosted and supported

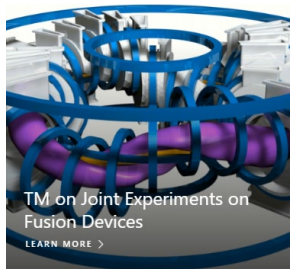
Organized and financially supported by IAEA



Fusion Energy School

11-22 May 2026,
Trieste, Italy



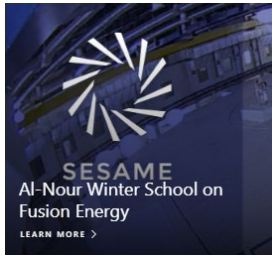


Fundamentals of Magnetic Confinement Fusion Design and Technology

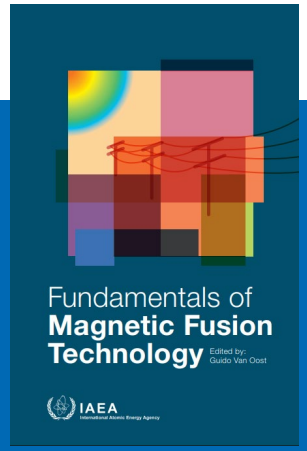
8-11 June 2026, Erice, Italy

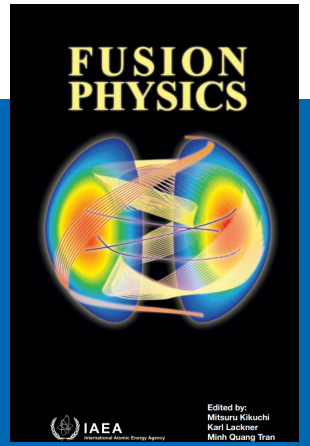






Complemented by key publications

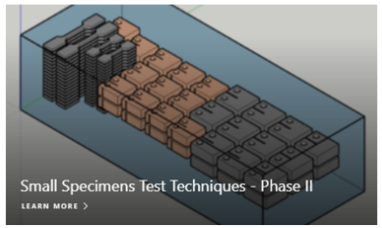




NA's coordinated research projects

Active Coordinated Research Projects

4yr project (2022-2026), developing SSTT guidelines



- Main test techniques: **tensile, creep, low cycle fatigue, fracture toughness, fatigue crack growth**
- Conduct **supporting experimental activities**
- **Enable standardization** – elaborate datasets and elements needed for approval by international authorities such as ASTM or ISO

The guidelines and experimental program aim to focus on **high-temperature applications** and **remote capabilities for hot-cell experiments.**

Active Coordinated Research Projects

5yr project (2022-2027), bridging MFE and IFE research



- **Open Science**, e.g. data/models openly accessible
- **FAIR** access to fusion data
- Develop research products to enable **cross-pollination**
- **Education, capacity building** in **ML-applied fusion science**

Fusion Data Lake under development.

NEW Coordinated Research Projects





4yr project (2027-2031)
networking laboratories for research and training with small MFC devices

5yr project (2026-2031)
translating plasma research into practical applications for societal, environmental and industrial benefit

CRPs – Atomic, molecular, PWI

https://amdis.iaea.org/CRP

2020-2025: Hydrogen Permeation in Fusion Materials, *continuation until end of* ***2026***

- To enhance knowledgebase and reduce uncertainties related to transport of hydrogen in fusion reactor components through modelling and benchmarking experiments.
- 21 participants, 15 Member States.

2022-2027: Data for Injected Impurities in Fusion Plasmas

- fundamental data for modelling the collisional processes of injected impurities, such as Ne, N, Ar (Kr, Xe)
- 9 institutions, 8 Member States

2023-2028: Molecules in Edge Plasmas

- fundamental data for formation, spectroscopic properties and reactions of molecular species in boundary plasmas, such as H_2, BH, WH, OH and other water-derived species
- 10 institutions, 9 Member States

2025-2031: Properties of W ions in Fusion plasmas ***new***

- 14 institutions, 9 Member States

2026-2030: Nuclear data for fusion *planned*

- **CRP Rationale**
  - Fusion neutronic simulations rely on relatively old data, while latest developments in fusion require modern nuclear data, including uncertainty quantification
  - New experimental data and simulation tools have become available to make the next-level fusion data library
- **Overall Objective(s)**
- Establish new nuclear data library for fusion

  Next version of **Fusion Evaluated Nuclear Data Library FENDL** (now in use by ITER)

  AI/ML driven evaluation techniques

  Highly dependent on nuclear reaction modeling and experimental nuclear reaction databases

  Will serve complete neutronics, activation and radiation damage analyses for different fusion devices (ITER, DEMO, IFMIF-DONES, etc.)

  Involve all relevant integral validation experiments
- **Expected Outcome(s)**
  - New fusion nuclear data library for neutron transport, activation and radiation damage
  - Computational tools for nuclear data handling, with and without AI/ML
  - Worldwide use of IAEA developed software and database for different fusion devices (ITER, DEMO, etc.)
- **Expected Participating Member States:** UK, France, Germany, China, USA, Spain, Japan

IAEA partners

Growing number of formalized partnerships!



















IAEA Collaborating Centres on Fusion





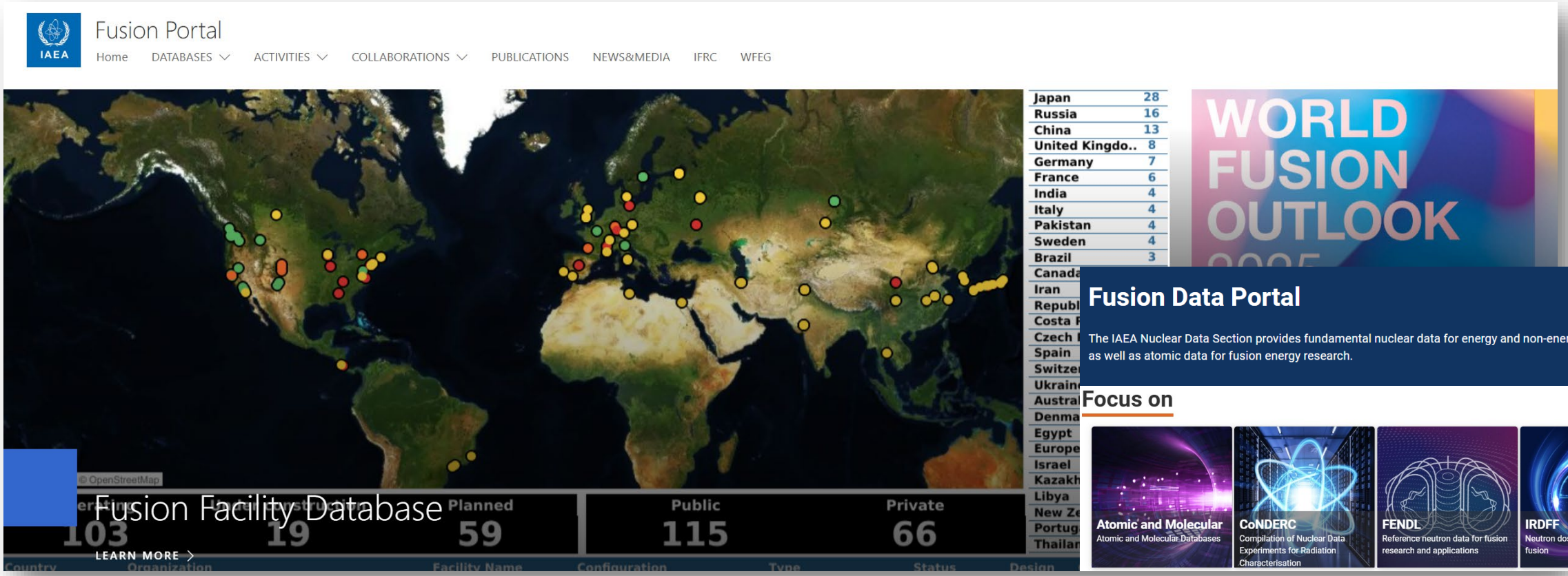




Supporting the implementation of the IAEA's fusion programme

Fusion Portal: centralized platform for the IAEA's fusion activities

https://nucleus.iaea.org/sites/fusion-portal



data, research projects, technical meetings, workshops, training schools & material, dedicated workspaces, news, media, and publications



Thank you!

M.Barbarino@iaea.org

Fusion Science Technical Lead

IAEA Department of Nuclear Sciences and Applications